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ECO-HYDROLOGICAL PROCESS SIMULATIONS WITHIN AN INTEGRATED SURFACE WATER-GROUNDWATER MODEL

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Integrated water resources management requires tools that can quantify changes in groundwater, surface water, water quality and ecosystem health, as a result of changes in catchment management. To address these requirements we have developed an integrated eco-hydrological modelling framework that allows hydrologists and ecologists to represent the complex and dynamic interactions occurring between surface water, ground water, water quality and freshwater ecosystems within a catchment. We demonstrate here the practical application of this tool to two case studies where the interaction of surface water and ground water are important for the ecosystem. In the first, simulations are performed to understand the importance of surface water-groundwater interactions for a restored riparian wetland on the Odense River in Denmark as part of a larger investigation of water quality and nitrate retention. In the second, we examine ecological impacts related to the flows and temperatures in the Silver Creek ecosystem that are important for the fish habitat. The Silver Creek ecosystem is controlled by large-scale interactions of surface water and groundwater systems in the Lower Wood River Valley, USA. In particular, the impacts of different catchment management scenarios on the ecosystem are evaluated.

INTRODUCTION

Within the context of the Water Framework Directive (WFD), water managers in Europe are being asked to address ecological status in the context of water resource and water quality management at the catchment scale. Key objectives of the WFD are:

- to protect and enhance the status of ***aquatic ecosystems*** (and terrestrial ecosystems and ***wetlands*** directly dependent on aquatic ecosystems)
- to promote ***sustainable water use*** based on long-term protection of available water resources
- to provide for sufficient supply of ***good quality surface water and groundwater*** as needed for sustainable, balanced and equitable water use

- to provide for enhanced ***protection and improvement of the aquatic environment*** by reducing / phasing out of discharges, emissions and losses of priority substances
- to contribute to mitigating the effects of ***floods*** and ***droughts***

These objectives, together with the requirements of the Floods and Groundwater directive mean that surface water and groundwater resources must be managed jointly while also ensuring the protection and improvement of water quality and the health of the associated freshwater dependent ecosystems. There are several key modelling challenges in addressing the complementary requirements of these different directives. The spatial and temporal distribution of catchment processes must be considered when linking management to aquatic habitat stressors [1]. It is necessary therefore to consider groundwater, surface water, water quality and ecosystems as an integrated system and develop modelling tools capable of representing these interactions. For example, the restoration of wetlands often requires an understanding of the interaction of surface water and groundwater quantity and quality. Furthermore while static indicator-based or statistical approaches are widely used for overall management, the actual ecosystem is highly dynamic and both the actual response to different threats and impact of measures will also be dynamic.

Surface water-groundwater interaction is an important process in riparian areas that can directly impact water budgets and allocations, as well as biogeochemical and ecological conditions and processes. Groundwater resources often have a complex dependency on adjacent water courses, wetlands and stream networks. Groundwater, on the other hand, is an important factor for surface water both in freshwater wetlands and in controlling low flows and maintaining environmental flows, particularly during periods of low rainfall. While there are a growing number of surface water- groundwater models, there are relatively few that include the capabilities to simulate ecosystem behaviour, river management and the ecological impacts of both river and catchment management [2].

This paper presents the development and application of an integrated hydro-ecological model to address these limitations. The hydrological component consists of the comprehensive process-based hydrological model, MIKE SHE which can represent flow and transport processes within the river network, groundwater, the unsaturated zone and surface flows. A generic ecological modelling tool (ECO Lab) has been incorporated in the MIKE SHE modelling framework to represent a range of water quality and ecological processes. The capabilities of this new tool have been evaluated using analytical solutions and laboratory data. As part of an on-going study of wetland nitrate retention, we investigate, on a local scale, the importance of surface water and groundwater interactions for flooding in a restored riparian wetland. The tool has also been applied on a catchment scale to develop an integrated hydro-ecological model to present large-scale surface water groundwater interactions in the Lower Wood River Valley, Idaho, US and the flows and temperatures in the spring-fed Silver Creek ecosystem within the Lower Wood Valley. In particular using temperature as an ecological indicator we can investigate the impacts of different catchment management strategies on the health of the Silver Creek ecosystem.

ECO-HYDROLOGICAL MODELLING

To develop a comprehensive eco-hydrological modelling tool, a coupled model was developed where the MIKE SHE modelling framework is used to model the flow and transport processes and ECO Lab is used to model water quality and ecological processes within the ground water, soil water, surface water, or channel system.

Distributed surface water-groundwater model – MIKE SHE

MIKE SHE is a process-based hydrological modelling system for representing flow, solute transport, water quality and other processes related to the land phase of the hydrological cycle at the catchment scale [3]. It represents the major flow processes including evapotranspiration, overland flow, unsaturated flow, groundwater flow, and channel flows as well as the interactions/feedback between these processes and has powerful capabilities for representing surface water/groundwater interactions [4]. MIKE SHE has been applied in numerous hydrological studies over a wide range of climates and hydrological regimes [5] at scales ranging from small catchments [6] to international river basins [7,8].

This process-based structure has been exploited to allow different representations of each process to be applied to a particular catchment [9]. This allows the modeller to choose between advanced or simplified process descriptions depending on the levels of spatial distribution and complexity required, as well as, the goals of the modelling study and the availability of field data. For example, more complex physics-based flow descriptions can be applied to the most important processes and simpler, faster, less data demanding methods for the less important processes or where rapid simulations are required such as in flood forecasting [10]. More complex physics-based process descriptions include comprehensive river and channel modelling representing flooding and wetlands [11,12].

Ecological modelling

The ecological modelling tool ECO Lab has been coupled to the MIKE SHE modelling framework. ECO Lab is an open process equation solver that calculates the rate of change of any type of state variable given any number of related variables, processes and forcings. The assumption is that the biological and chemical transformation processes affecting state variables (ES_i) in an ecosystem can be formulated as a set of coupled ordinary differential equations:

$$\frac{d(ES_i)}{dt} = \sum_{i=1}^{n} PROCESS_i \qquad (1)$$

The process functions can consist of mathematical functions, built-in functions, numbers, forcings, constants, and state variables. The arguments are separated by operators such as +-*/, and the syntax also supports other types of expressions such as 'IF THEN ELSE' expressions. The mathematical and built-in functions are functions that are already defined in ECO Lab and can be used directly by referring to them. ECO Lab has a number of documented models (referred to as “templates”) that describe well-known processes such as eutrophication templates that describe nutrient cycling, phytoplankton and zooplankton growth, growth and distribution of rooted vegetation and macro algae in addition to simulating oxygen conditions. A user can also formulate customized process descriptions. ECO Lab relies on other models to calculate flow and transport processes and acts as a post-processor at each time step to calculate the process dynamics, in this case MIKE SHE. In this manner spatial and temporal simulation of a wide range of water quality and ecosystem response studies can be performed.

ECO-HYDROLOGICAL MODELLING

The coupled eco-hydrological modelling tool is referred to here as MIKE SHE-ECOLAB. To evaluate this tool, simulation results have been compared to analytical solutions and laboratory experiments. Tuxen *et al.* [13] examine the fate of selected pesticides under aerobic conditions in column experiments using aquifer material and low concentrations of pesticides. Their results include both experimental data and simulations using a solute transport model with kinetic sorption and degradation processes. Figure 1 compares the simulations of MIKE SHE-ECOLAB with one of these experiments.

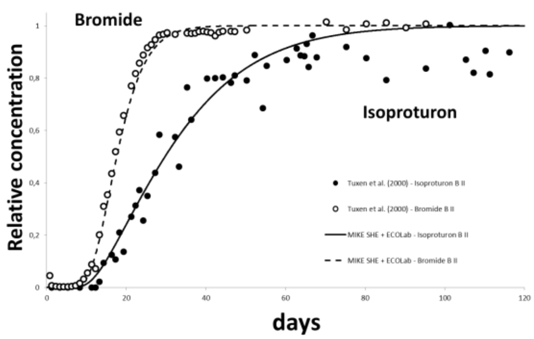

Figure 1. Comparison of the breakthrough curves simulated with MIKE SHE-ECOLAB and the experimental results of Tuxen *et al.* [13] for bromide and the pesticide isoproturon.

Restored riparian wetland

A study of the retention of nitrate in a wetland area is currently being undertaken with MIKE SHE-ECOLAB. The study area is a restored flood plain [14] on the Odense River, where an area of approximately 125 ha has been modified by re-meandering and reducing the flow capacity of the formerly straightened river channel, Figure 2. The restored area has also been transformed from intensively cultivated land to permanently grazed meadows following restoration. Poulsen et al [14] provide a more detailed description of this study area. They investigate using a two-dimensional hydro-dynamic model the floodplain hydraulics in order to link this to the deposition of sediment, organic matter and phosphorous.

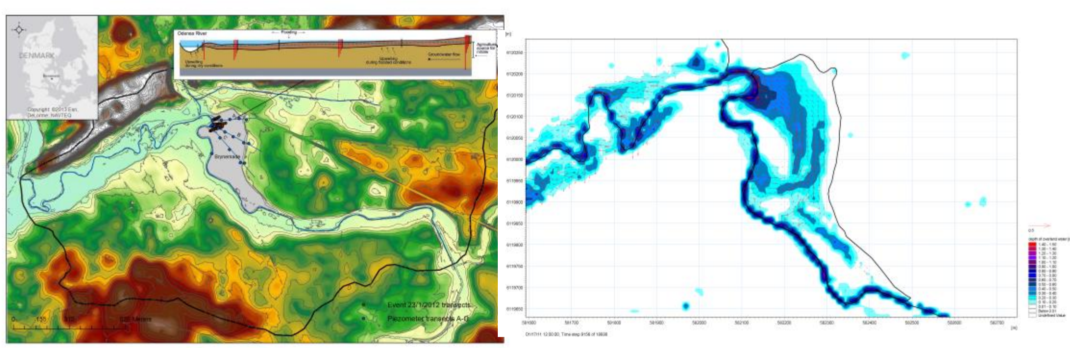

Figure 2. An overview of the restored river model area (left). The wetland area of interest is highlighted in grey. Simulated wetland flooding is shown for the 17 January 2011 using a numerical grid size of 12.5 m (right). Arrows show the direction and magnitude of flow.

We have applied the MIKE SHE to examine both surface water flow dynamics and also to investigate the importance of surface water-groundwater interactions during flooding. Figure 2 shows preliminary simulations of the flooding behaviour during a heavy rainfall event. modelling. Our initial results (Figure 3) show a complex exchange of water; the river and floodplain providing inflows to the wetland directly, and indirectly via groundwater, the surrounding aquifer acting first as a sink and then as a source replenishing the wetland during the flood and finally the wetland contributing to the river baseflow. Future work will compare these simulations with measurements of water and flows in the river and water levels and groundwater levels in the flood plain measured along a number of transects, (Figure 2), to investigate the uncertainty and dynamics of the water balance and examine the nitrate retention processes within this riparian wetland.

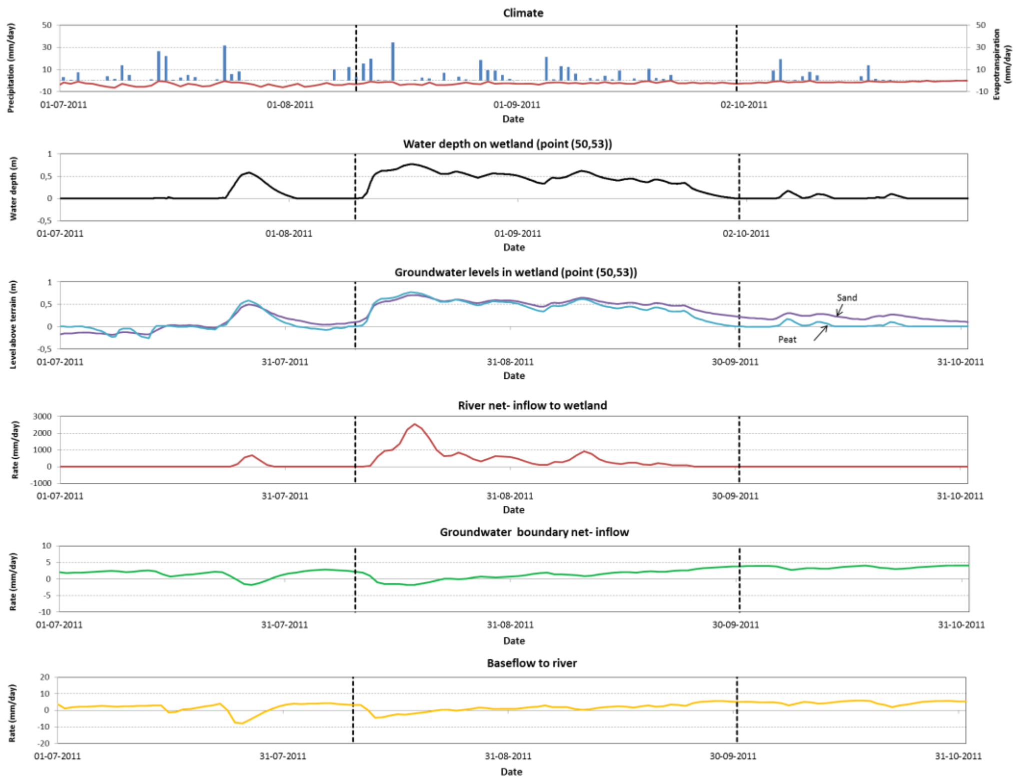

Figure 3. Selected components of the wetland water balance during the flood event in August 2011 (the flood period is marked with dashed black lines).

Silver Creek ecosystem

Recently Loinaz *et al.* [15] applied the MIKE SHE-ECOLAB tool to investigate the large-scale surface water-ground water interaction in the Big Wood River–Silver Creek surface water and aquifer system and the impacts on different management strategies on the flows and temperatures in the Silver Creek ecosystem [16]. The Wood River Valley Aquifer is located between two surface water basins (Figure 4) and receives seepage flow from the Big Wood River. Downstream of the aquifer, Silver Creek is a spring-fed system abundant in wildlife and is not only a valuable trout habitat but a world-renowned fly-fishing destination. As a spring-fed system, it is necessary to understand the large-scale surface water-groundwater interactions to predict the fluxes in the system. There are several environmental stressors affecting the ecosystem such as changes in channel morphology, fine sediments, water temperature, and nutrients that are influenced by land use changes in the catchment. Higher temperatures and decreased flows in Silver Creek during summer are threatening the aquatic habitat [16]. Temperature is an important ecological indicator for Silver Creek that is critical for the fish population.

To assess the impact of different catchment management strategies, integrated surface water groundwater models were developed for both the Big Wood River and Silver Creek and calibrated to represent the fluxes and temperatures [15]. The large-scale regional model developed for the Big Wood Basin was used to estimate groundwater fluxes to Silver Creek. A local integrated model of the Silver Creek system was then established using the regional model results as boundary conditions. Using ECOLAB, a river temperature model was developed and tested against analytical solutions [15] and then calibrated against data from the Silver Creek basin. Figure 5 illustrates the ability of the coupled model to capture the level and dynamics of temperature at a single site in Silver Creek.

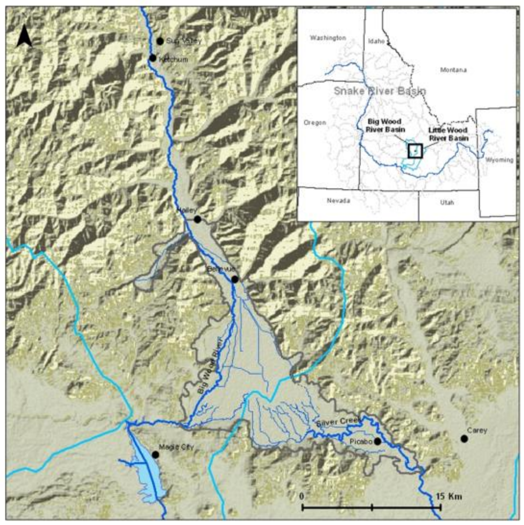

Figure 4. The location and topography of the Big Wood River and Silver Creek.

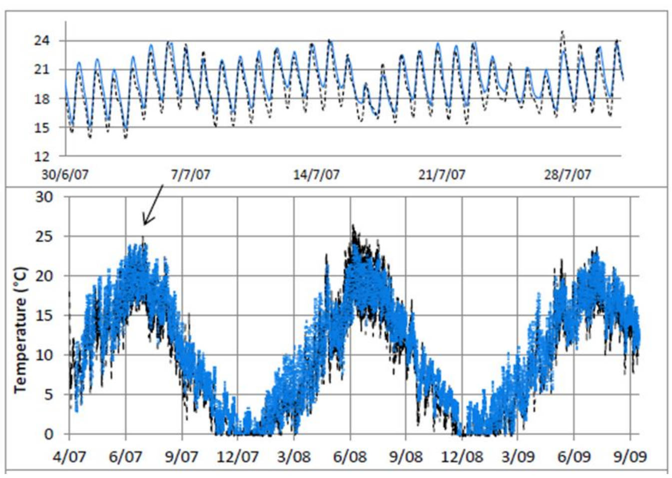

Figure 5. The simulated and observed river temperatures for a single station in Silver Creek.

This river temperature model was then used to investigate how land use and water use affect the temperature distribution. It was possible with the model to represent the current state and the original state of the system as baselines for different restoration measures, see Figure 6. Loinaz et al. [16] simulate the relative impacts of different stressors on the hydrological processes, stream temperature, and fish growth. Interestingly, their results indicate that temperature dynamics, rather than point statistics, determine optimal growth conditions for fish, [16].

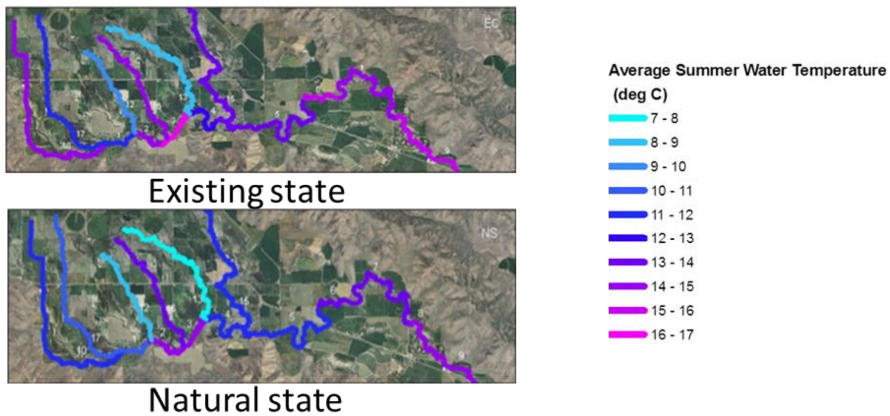

Figure 6. Comparison of the simulated existing and natural state in terms of average daily summer water temperature.

CONCLUSIONS

Surface water-groundwater interactions are important for water budgets and allocations, flooding, river and wetland restoration and the biogeochemical and ecological conditions and processes in riparian areas. The combination of MIKE SHE and ECO Lab provides the capability to quantify effects of catchment management on groundwater, surface water, water quality and ecosystem health in an integrated manner. In the restored river case, our preliminary results suggest that river flows, floodplain flows and groundwater all contribute to the wetland water balance during flood events. Future work is aimed at evaluating the model against field observations and then to examine water quality and ecological processes in the restored wetland. In modelling the Silver Creek ecosystem, temperature is an important ecological variable that is critical for the fish population. A proper understanding of the effect of different management strategies within this basin depends on both an accurate representation of the flow processes and water management in the Wood River Valley. The simulations indicate that temperature dynamics, rather than point statistics, determine optimal growth conditions for fish.

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